Gamma-ray line emission from OB associations and young open clusters

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Abstract. OB associations and young open clusters constitute the most prolific nucleosynthesis sites in our Galaxy. The combined activity of stellar winds and core-collapse supernovae ejects significant amounts of freshly synthesised nuclei into the interstellar medium. Radioactive isotopes, such as ^{26}Al or ^{60}Fe, that have been co-produced in such events may eventually be observed by gamma-ray instruments through their characteristic decay-line signatures. However, due to the sensitivity and angular resolution of current (and even future) γ-ray telescopes, only integrated γ-ray line signatures are expected for massive star associations.

In order to study such signatures and to derive constraints on the involved nucleosynthesis processes, we developed a multi-wavelength evolutionary synthesis model for massive star associations. This model combines latest stellar evolutionary tracks and nucleosynthesis calculations with atmosphere models in order to predict the multi-wavelength luminosity of a given association as function of its age.

We apply this model to associations and clusters in the well-studied Cygnus region for which we re-determined the stellar census based on photometric and spectroscopic data. In particular we study the relation between 1.809 MeV γ-ray line emission and ionising flux, since the latter has turned out to provide an excellent tracer of the global galactic 1.809 MeV emission. We compare our model to COMPTEL 1.8 MeV γ-ray line observations from which we derive limits on the relative contributions from massive stars and core-collapse supernovae to the actual ^{26}Al content in this region. Based on our model we make predictions about the expected ^{26}Al and ^{60}Fe line signatures in the Cygnus region. These predictions make the Cygnus region a prime target for the future INTEGRAL mission.

EVOLUTIONARY SYNTHESIS MODEL

Our evolutionary synthesis model is based on the multi-wavelength code described in [6,1], enhanced by the inclusion of nucleosynthesis yields. In summary, the evolution of each individual star in a stellar population is followed using Geneva evolutionary tracks with enhanced mass-loss rates [7]. In our present implementation, and similar to [6,1], stellar Lyman continuum luminosities are taken from

FIGURE 1. ^{26}Al yield (left) and equivalent O7V star ^{26}Al yield (right) as function of association age. The hatched area indicates the COMPTEL measurement of $Y_{26}^{\rm O7V} = (1.0 \pm 0.3)\, 10^{-4}\ M_{\odot}$.

[9,4]. Note, however, that modern atmosphere models including the effects of line blanketing and stellar winds predict enhanced ionising fluxes with respect to these models, hence our predicted ionising luminosities should be considered as preliminary and possibly are somewhat too low[1]. At the end of stellar evolution, stars initially more massive than $M_{\rm WR} = 25\ M_{\odot}$ are exploded as Type Ib supernovae, while stars of initial mass within $8 M_{\odot}$ and $M_{\rm WR}$ are assumed to explode as Type II SNe. Nucleosynthesis yields have been taken from [8] for the pre-supernova evolution and from [12,13] for Type II and Type Ib supernova explosions, respectively. Note that Type II SN yields have only been published for stars without mass loss and Type Ib yields have only been calculated for pure Helium stars. In order to obtain consistent nucleosynthesis yields for Type II supernovae we followed the suggestion of [5] and linked the explosive nucleosynthesis models of [12] to the Geneva tracks via the core mass at the beginning of Carbon burning. For Type Ib SN we used the core mass at the beginning of He core burning to link evolutionary tracks to nucleosynthesis calculations.

Evolutionary synthesis models were calculated using a stochastic initial mass function where random masses were assigned to individual stars following a Salpeter initial mass spectrum ($d \log \xi / d \log M = -1.35$) until the number of stars in a given mass-interval reproduces the observed population. Typical results for a rich OB association (51 stars within $15 - 40\ M_{\odot}$) are shown in Fig. 1. ^{26}Al production turns on at about $1 - 2$ Myr when the isotope starts to be expelled by stellar winds into the interstellar medium. Stellar ^{26}Al production reaches its maximum around 3 Myr when the most massive stars enter the Wolf-Rayet phase. Explosive nucleosynthesis sets on around 4.5 Myr for Type Ib and around 7 Myr for Type

1) We currently are implementing the CoStar atmosphere models of [11] in our code that consistently treat the stellar structure and atmosphere and include line blanketing and stellar winds.

II supernovae, leading to a second peak in the ^{26}Al yield around 8 Myr. After this peak, a slightly declining ^{26}Al yield is maintained by Type II explosions until the last Type II SN exploded around 20 Myr. Afterwards, the exponential decay quickly removes the remaining ^{26}Al nuclei from the ISM.

We also calculated the time-dependent ionising luminosity ($\lambda < 912$ Å) of the population from which we derived the equivalent O7V star ^{26}Al yield $Y_{26}^{\rm O7V}$. This quantity measures the amount of ^{26}Al ejected per ionising photon normalised on the ionisation power of an O7V star. The analysis of COMPTEL 1.809 MeV data suggests a galaxywide constant value of $Y_{26}^{\rm O7V} = (1.0 \pm 0.3)\,10^{-4}\ M_{\odot}$ [3]. Interestingly, the COMPTEL value is only reproduced for a very young population during a quite short age period ($2.5 - 5$ Myrs). For younger populations too few ^{26}Al is produced with respect to the ionising luminosity, leading to much lower equivalent yields. For older populations the ionising luminosity drops rapidly, resulting in much higher $Y_{26}^{\rm O7V}$ values. Thus, the equivalent O7V star ^{26}Al yield is a quite sensitive measure of the population age. In particular, the measurement of $Y_{26}^{\rm O7V}$ for individual OB associations or young open clusters provides a powerful tool to identify the dominant ^{26}Al progenitors.

APPLICATION TO THE CYGNUS REGION

We applied our evolutionary synthesis model to the Cygnus region from which prominent 1.809 MeV line emission has been detected by COMPTEL [2]. In [2] the authors modelled ^{26}Al nucleosynthesis in Cygnus by estimating the contribution from individual Wolf-Rayet stars and supernova remnants that are observed in this region. This approach, however, suffers from considerable uncertainties due to the poorly known distances to these objects. In this work we performed a complete census of OB associations and young open clusters in the Cygnus region. Individual association or cluster distances have been estimated by the method of spectroscopic parallaxes, ages have been determined by isochrone fitting. Distance and age uncertainties have also been estimated and were incorporated in the analysis by means of a Bayesian method. The richness was estimated for each association or cluster by building H-R diagrams for member stars and by counting the number of stars within mass-intervals that are probably not affected by incompleteness or evolutionary effects. In total we included 6 OB associations and 19 young open clusters in our analysis which house 94 O type and 13 Wolf-Rayet stars.

For each OB association or cluster, 100 independent evolutionary synthesis models were calculated that differ by the actual stellar population that has been realised by the random sampling procedure. In this way we include the uncertainties about the unknown number of massive stars in the associations that have already disappeared in supernova explosions. From these samples the actual age and distance uncertainties are eliminated by marginalisation, leading to a probability distribution for all quantities of interest. Note that in this approach an age uncertainty is equivalent to an age spread in the cluster formation, hence the possibility of

non-instantaneous star formation has been taken into account. The results for all individual associations have been combined by marginalisation to predictions for the entire Cygnus region.

The predicted equivalent O7V star ^{26}Al yield amounts to $(0.3 - 1.2)\,10^{-4}\ M_{\odot}$ and is compatible with the COMPTEL observation, pointing to an extremely young population that is at the origin of ^{26}Al. Indeed, while 90% of the ^{26}Al is produced in our model by stellar nucleosynthesis (during the main sequence and subsequent Wolf-Rayet phase), only 10% may be attributed to explosive nucleosynthesis, mainly in Type Ib SN events. This is also reflected in the low ^{60}Fe yields ($(0 - 7)\,10^{-8}$ ph cm^{-2} s^{-1}) that are predicted by our model since ^{60}Fe is assumed to be only produced in supernovae.

However, in absolute quantities, our model underestimates the free-free intensity in Cygnus by about a factor 3 while the total ^{26}Al flux is low by a factor of 5. This points towards a possible incompleteness of our massive star census which has been based on surveys of OB associations and young open clusters in Cygnus available in the literature. Indeed, while we identify only 95 OB stars in Cyg OB2, [10] estimated 400 OB members in this association, indicating only 25% completeness of our census. Taking 25% as a typical completeness fraction for our OB association census and assuming that the young open cluster census is complete, we obtain a free-free intensity of 0.25 mK and an ^{26}Al flux of $4.3\,10^{-5}$ ph cm^{-2} s^{-1} – values that are in fairly good agreement with the observations (0.26 mK from DMR microwave data and $(7.9 \pm 2.4)\,10^{-5}$ ph cm^{-2} s^{-1} from COMPTEL 1.8 MeV observations; see Plüschke et al., these proceedings). However, we do not predict any noticeable amount of ^{60}Fe for the Cygnus region – a prediction which hopefully will be soon verified by the INTEGRAL observatory. We would like to stress that INTEGRAL has the potential to partially resolve some OB associations and young open clusters in the nearby Cygnus region, and thus may provide important new insights in massive star nucleosynthesis in this area.

REFERENCES

1. Cerviño, M. and Mas-Hesse, J.M., 1994, A&A, 284, 749
2. Del Rio, E., et al. 1996, A&A, 315, 237
3. Knödlseder, J., 1999, ApJ, 510, 915
4. Kurucz, R.L., 1979, ApJS, 40, 1
5. Maeder, A., 1992, A&A, 264, 105
6. Mas-Hesse, J.M. and Kunth, D., 1991, A&AS, 88, 399
7. Meynet, G., et al. 1994, A&AS, 103, 97
8. Meynet, G., et al. 1997, A&A, 320, 460
9. Mihalas, D., 1972, NCAR-TN/STR-76
10. Reddish, V.C., Lawrence, L.C. and Pratt, N.M., PROE, 5, 111
11. Schaerer, D. and de Koter, 1997, A&A, 322, 598
12. Woosley, S. and Weaver, T.A., 1995, ApJS, 101, 181
13. Woosley, S., Langer, N. and Weaver, T.A., 1995, ApJ, 448, 315